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Temperature Behavior of Thin Film Varactor

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14. ABSTRACT
The low loss varactor (voltage tunable capacitor) would revolutionize the wireless communication, sensing, and detecting industries. Temperature behavior plays a critical role in barium strontium titanate (BST) thin-film varactors. In this report, the behaviors of resonant frequency as a function of test time were investigated and discussed. The temperature behaviors of both metal organic deposition (MOD) and pulsed laser deposition (PLD) thin-film varactors were studied from –30 to 80 °C. The temperature coefficients of thin-film varactors were modeled and calculated.

15. SUBJECT TERMS
MOD, PLD, BST thin film, varactor

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1. Introduction

In wireless communication, systems should operate over multiple frequency bands and provide an enhanced signal-to-noise ratio. These goals can be achieved by having electronic tunability in the radio frequency (RF) part of the radios. Electronic tuning is the ability by which electronic devices operate over a wide frequency range. It can allow a single filter to tune over multiple frequency bands, a voltage tunable oscillator (VTO) to accommodate a wide range of frequencies for the synthesizer, and a scanning antenna to position a beam, on command, anywhere within its sector of operation. Traditionally, electronic tuning has been achieved through ferrite or semiconductor diodes. Commercially available ferrite products are expensive and bulky. Also, the power consumption of these devices is prohibitive. Further, semiconductor junction diodes are restricted in their range of linear response to input power. For high frequency applications, semiconductor-based technology for products like electronic scanning antennas is also very expensive.

These limitations in existing solutions have paved the way for new approaches to address low-cost electronic tuning. One of the most promising approaches is the use of tunable dielectric materials. The existence of low loss voltage tunable dielectric materials would revolutionize the industry of microwave components and antennas. "Tunable" refers to the ability to change dielectric constant by applying an electric field. This ability in the microwave component field enables a single component to operate over multiple frequencies by simply changing the input voltage. The low power consumption in operating devices fabricated from these voltage tunable dielectrics is an additional benefit. Varactors are voltage tunable capacitors in which the capacitance is dependent on a voltage applied. Temperature behavior plays a critical role in thin-film varactors (*1–5*). In this report, we investigate a test method for determining the temperature behavior of thin-film varactors, discuss the relaxation time to a stable state, and provide the experimental results.

2. Experimental Approach

Strain-relieved and epitaxially grown barium strontium titanate ($Ba_{1-X}Sr_XTiO_3$ or BST) ($x = 0.3–0.6$) films on (100) magnesium oxide (MgO) were prepared by metal organic deposition (MOD) and pulsed laser deposition (PLD) (*6*).

MOD has the advantages of ease of composition adjustment and small capital cost. The main features of this process are room-temperature chemical precursor solution preparation, short preparation time, readily available precursors, high stability, and compatibility with semiconductor-fabrication technology. The BST MOD precursors selected as the source of the

solution are $Ba(thd)_2$ trietherdiamine adduct $[(C_{32}H_{62}N_2O_7)Ba]$, $Sr(thd)_2$ trietherdiamine adduct $[(C_{32}H_{62}N_2O_7)Sr]$, and $Ti(O\text{-}IPr)_2(thd)_2$ (all from Advanced Technology Materials, Inc.). The spin-coated films were baked on hot plate with 350 °C for 10 min and finally crystallized films were formed under 750 °C for 1 h.

PLD provides excellent target stoichiometry transfer of complex oxide ceramics to high-quality thin films. During this process, the focused output (laser fluence of 1.9 J/cm^2) of a short-pulse (full width at half maximum [FWHM] of ~20 ns) excimer laser was used to flash-evaporate a target. The rapid heating and evaporation of the solid target by the laser resulted in the formation of an energetic plasma plume, which was transported through an ambient gas (200 mTorr O_2) to the surface of a 5-cm away heated substrate (770 °C) (*1, 3, 4*).

The temperature behavior of thin-film varactor was done in Delta 9028 temperature-controlled chamber. It has electric heating and nitrogen cooling provided by a liquid nitrogen tank. The sample and its fixture were installed within this chamber. For each temperature change, the sample sits in the chamber at least 45 min before measurement. There is a “warming” period in the data collection process, during which one applies bias voltages of 0, 50, 100, 50, and 0 V, correspondingly. After the bias voltage returns to 0 V, the system is ready for measurement.

3. Results and Discussion

3.1 Resonant Frequency as a Function of Test Time

After each bias voltage switch, I found that the resonant frequency of the varactor was continuously changing. As an example, resonant frequency as a function of test time for a PLD varactor is shown in figure 1. The test was done at a temperature of 0 °C and a bias voltage of 0 V. An exponential decay behavior is observed. Figure 2 shows calculated capacitance as a function of test time.

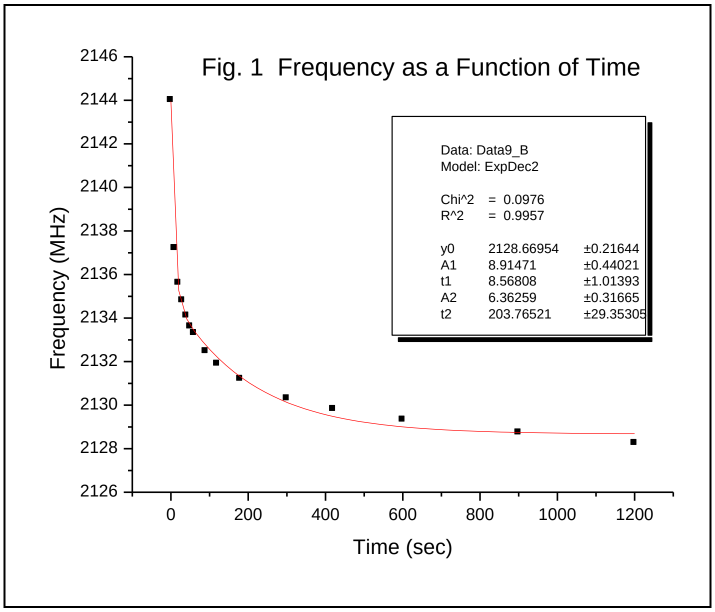

Figure 1. PLD varactor's frequency as a function of time.

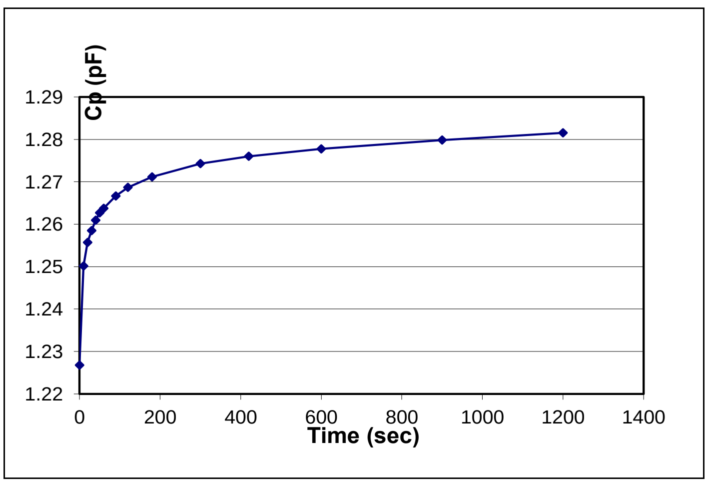

Figure 2. Capacitance as a function of test time.

The time behavior of resonance frequency at 50 V (switched from 0 V) and 100 V (switched from 50 V) are different. The results are shown in figures 3 and 4, respectively. An exponential increase for both measurements is observed.

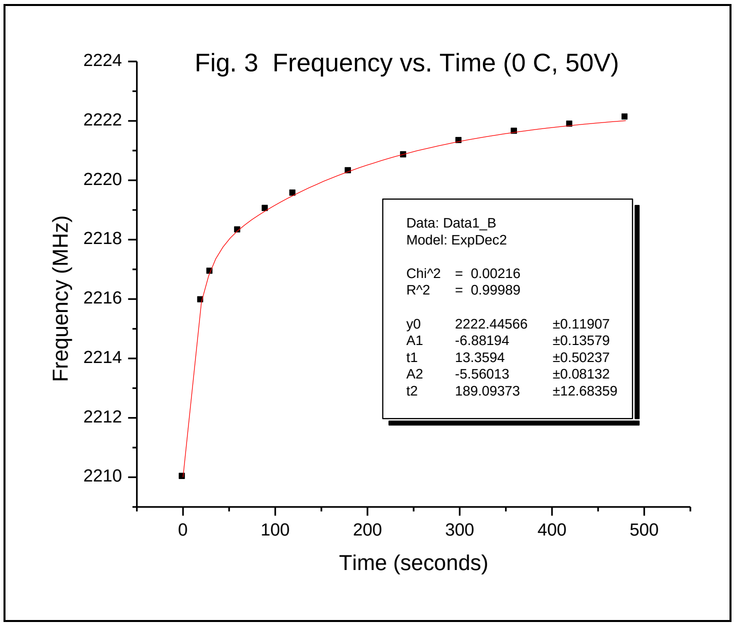

Figure 3. Frequency as a function of time (0 °C, 50 V).

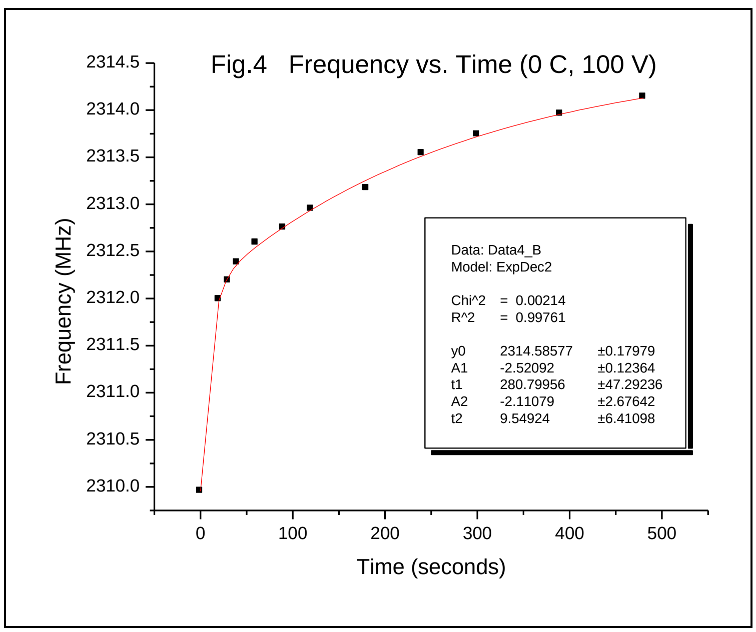

Figure 4. Frequency as a function of time (0 °C, 100 V).

Figures 1, 3, and 4 indicate that if one takes the data at different times after the bias voltage switch, the data would be different. For example, there was an 8–25% tuning difference between one set of data taken immediately after it was switched to the desired bias voltage versus one that was taken after waiting 5 min.

It was found that these plots could be fitted by a second-order exponential decay function:

$$\text{Frequency} = y_0 + A_1 \exp(-t/t_1) + A_2 \exp(-t/t_2), \quad (1)$$

where t is the time, and t_1 and t_2 are time constants. Fitted parameters are also shown in figures 1, 3, and 4, respectively—the fitting is very good. All three R^2's are better than 0.998. The second-order exponential fitting suggests that there exist two processes. Both have exponential decay (or increase) behaviors. The time constants of these two processes are around 10 and 220 s.

If the BST thin-film varactor sits in the environmental chamber for a long time, the temperature (a measure of random translation motion) of the crystal lattice, sample, and chamber all become equal. As observed, when applying a bias voltage, a lattice shift or displacement of the BST crystal structure would occur. The crystal structure would go back to normal (no distortion) once the bias voltage was removed (from 50 to 0 V). The shifted or displaced structure would exhibit a higher energy than the normal structure. The extra energy would then transfer to the lattice vibration energy. Thus, the vibration temperature would be higher than the random translational temperature. Thus, the first process necessary is the relaxation of the sample from vibration to translation. This relaxation process causes the local temperature increase (and higher frequency reading).

The second process is the energy transfer from local higher temperature to the environmental temperature (the cooling down process by nitrogen). It is suggested that the shorter time t_1 constant belongs to local heating or cooling by environment and the longer time constant t_2 fits into relaxation from vibration to random translation movements.

I determined that one should wait 40 to 45 s before taking the measurement data. The reasons are (1) waiting 40 to 45 s reduces the error ranges of capacitance and tuning to less than 3% and 6%, respectively, which is acceptable; and (2) 40 to 45 s is more than four times the shorter time constant (10), which corresponds to a 98% completion of the relaxation process, in other words, the error will be less than 2%.

3.2 Temperature Behavior of MOD Thin-film Varactor

The temperature behaviors of MOD thin films are shown in figure 5. The MOD samples have composition of 60.01 with tungsten doping on an MgO substrate. Figure 5a shows the tuning behavior of the MOD thin-film varactor. Tuning decreases as temperature increases. Figure 5b shows capacitance variation as a function of temperature. Note that there is a significant change in capacitance at a 0-V bias; however, the capacitance changes at a 50- and 100-V bias are minor. The temperature coefficient of MOD varactor is –1230 ppm at a 50-V bias and 154 ppm at a 100-V bias. Figure 5c shows the Q variation.

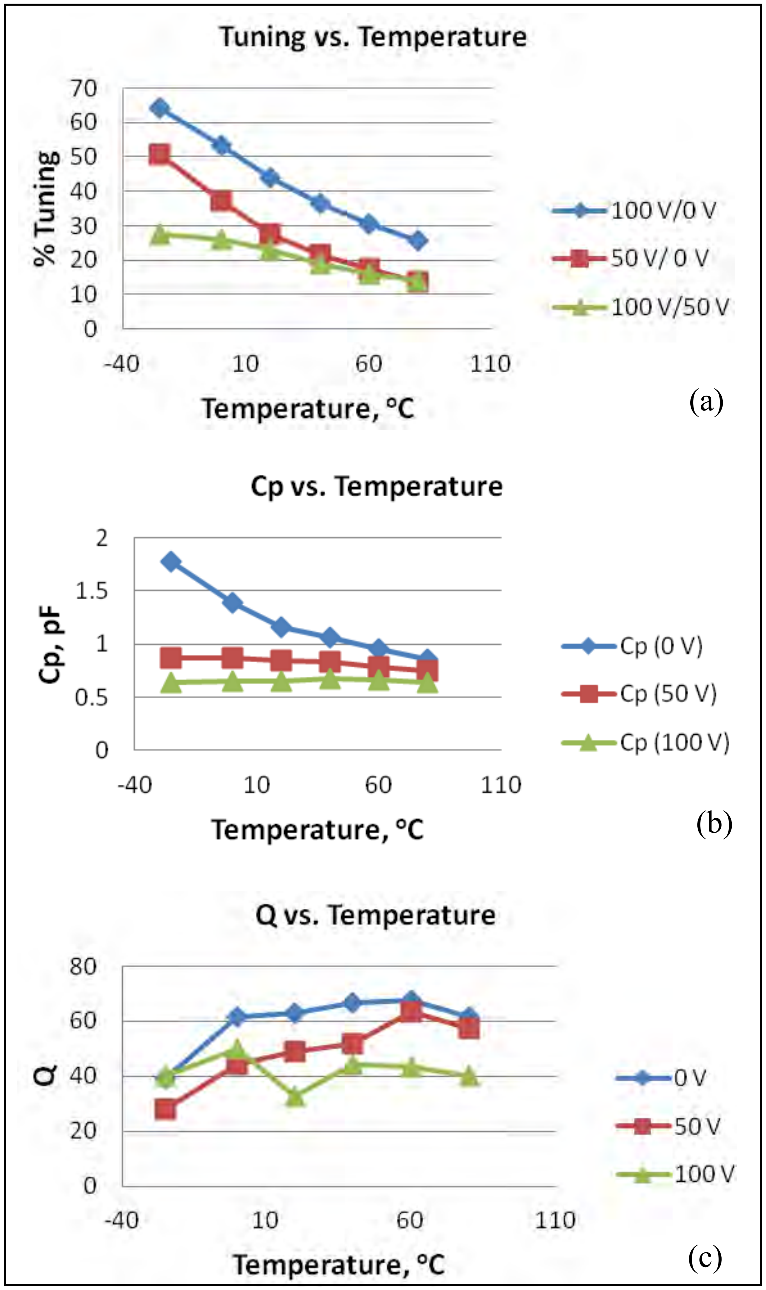

Figure 5. MOD samples: (a) percentage of tuning of capacitance, (b) capacitance, and (c) Q of the varactor as a function of temperature at 2 GHz and DC bias voltages up to 100 V.

3.3 Temperature Behavior of PLD Thin-film Varactor

The temperature behaviors of PLD thin films are shown in figure 6. The PLD samples have composition of 60.01 with tungsten doping on an MgO substrate. Figure 6a shows the tuning behavior of the PLD thin-film varactor. Tuning decreases as temperature increases. Figure 6b shows capacitance variation as a function of temperature. The temperature behaviors are similar

to those of the MOD thin films. The temperature coefficient of PLD varactor is 2600 ppm at a 50-V bias and 604 ppm at a 100-V bias. Figure 6c shows the Q variation.

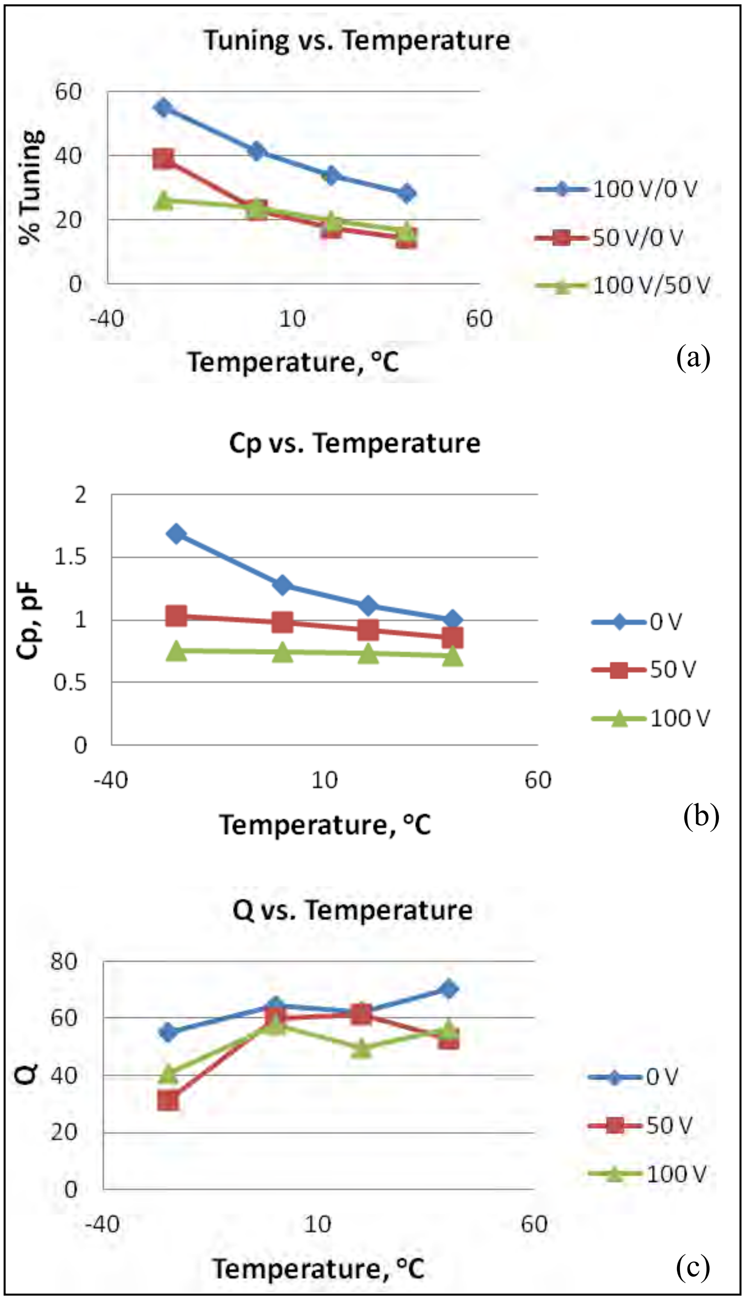

Figure 6. PLD samples: (a) percentage of tuning of capacitance, (b) capacitance, and (c) Q of the varactor as a function of temperature at 2 GHz and DC bias voltages up to 100 V.

4. Conclusions

Exponential decay or increase behavior is observed by the resonant frequency of a varactor as a function of test time. I determined that one should wait 40 to 45 s before taking the measurement data.

The following are the results of temperature behaviors of thin film varactors:

- The temperature coefficient of MOD thin film varactor is –1230 ppm at a 50-V bias and 154 ppm at a 100-V bias.
- The temperature coefficient of PLD varactor is 2600 ppm at a 50-V bias and 604 ppm at a 100-V bias.

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List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
BST	barium strontium titanate
Cp	capacitance
MgO	magnesium oxide
MOD	metal organic deposition
PLD	pulsed laser deposition
Pt	platinum
Q	quality factor
VTO	voltage tunable oscillator

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